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Necessary Conditions for Multi-Domain Indoor Environmental Quality Standards

Ardeshir Mahdavi [1,*], Christiane Berger [1], Veselina Bochukova [1], Leonidas Bourikas [2], Runa T. Hellwig [3], Quan Jin [4], Anna Laura Pisello [5] and Marcel Schweiker [6]

1 Department of Building Physics and Building Ecology, TU Wien, 1040 Vienna, Austria; christiane.berger@tuwien.ac.at (C.B.); veselina.bochukova@tuwien.ac.at (V.B.)
2 Imagination Lancaster, School of Architecture, Lancaster University, Lancaster LA1 4YW, UK; l.bourikas@lancaster.ac.uk
3 Department of Architecture, Design and Media Technology CREATE, Aalborg University, 9000 Aalborg, Denmark; rthe@create.aau.dk
4 Department of Architecture and Civil Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden; quan.jin@chalmers.se
5 Department of Engineering, University of Perugia, 06125 Perugia, Italy; anna.pisello@unipg.it
6 Institute for Occupational, Social and Environmental Medicine, RWTH Aachen University, 52074 Aachen, Germany; mschweiker@ukaachen.de
* Correspondence: amahdavi@tuwien.ac.at; Tel.: +43-1-58801-27003

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Abstract: A discussion of sustainability in architecture cannot be meaningfully carried out without the inclusion of most buildings' central purpose, namely the provision of indoor environments that are accommodating of occupants' needs and requirements. To this end, building designers and operators are expected to demonstrate compliance with codes and standards pertaining to indoor environmental quality (IEQ). However, the majority of conventional IEQ standards, codes, and guidelines have a single-domain character, in that they address IEQ in terms of a number of isolated domains (i.e., thermal, visual, acoustic, air quality). In this context, the present contribution explores the current state of multi-domain IEQ evaluation approaches and the necessary conditions for their further development and application. Toward this end, a number of common building rating schemes were selected and analyzed in detail. The results of this assessment imply the necessity of both short-term improvements of the existing schemes in terms of the transparency and plausibility of the applied point allocation and weighting strategies and the fundamental need for a deeper empirically grounded understanding of the nature of occupants' perception of and behavior in the built environments.

Keywords: indoor environmental quality; codes; standards; multi-domain; human factor; architecture; building; sustainability rating

1. The Need for Integrative Occupant-Centric Standards

As with other fields, the sustainability discourse in the field of built environment needs to address not only the environmental and economic aspects, but also the social—i.e., human-centric—dimension of building design and operation. Ultimately, the main purpose of most buildings is the provision of indoor environments that are accommodating of occupants' needs and requirements. Human requirements in design and operation of buildings can be adequately discussed in the context of built environments' effectiveness and efficiency [1]. Whereas provision of conditions conducive to people's health, comfort, satisfaction, and productivity are associated with buildings' effectiveness, such conditions must be provided in an efficient manner from the point of energy and environmental impact. In other words, buildings are expected to provide a high degree of habitability (the effectiveness requirement) in an energy and resource conserving manner (the efficiency requirement).

To this end, building designers and operators often rely on various codes, standards, guidelines, and other forms of assessment procedures and evaluation schemes. Deployment scenarios of such resources typically involve both effectiveness and efficiency considerations. The adequate (effective) attributes of designs (mainly in view of indoor-environmental quality) are to be realized in an efficient manner (e.g., in terms of energy and resource use). Thus, codes, standards, guidelines, and other building evaluation and certification instruments should ideally help planners and operators to find out if:

i. A design proposal or an operation regime is effective, i.e., if it leads to a more habitable environment, and
ii. The provision of habitability is accomplished in an environmentally and economically efficient manner.

Particularly, the evaluation of buildings' effectiveness necessitates a deep understanding of habitability requirements, or—to use a more common parlance—buildings' indoor environmental quality (IEQ) as relevant to occupants' needs and expectations. It is common knowledge that IEQ requirements are diverse and multifaceted. As such, they pertain to multiple domains (i.e., thermal, visual, indoor air quality, acoustic) and disciplines (e.g., architecture, mechanical engineering, psychology, physiology). There is also a general agreement—albeit at a theoretical level—that achieving high-performance built environments requires a deep integration of such diverse IEQ domains. Nonetheless, most conventional standards, codes, and guidelines have arguably a single-domain character, in that they address IEQ in terms of a number of isolated domains. A tacit assumption thereby appears to be that achieving "best performance" in individual domains results in an overall optimum performance at the building level. Recently, efforts are being made to provide the necessary knowledge base for formulation of integrated multi-aspect building design support resources and procedures [2]. In this context, the present contribution explores the current state of multi-domain IEQ evaluation approaches and the necessary conditions for their further development and application.

2. Approaches to the Evaluation of Buildings' IEQ

As discussed in the previous section, the design, construction, and operation of buildings are expected to address multiple quality requirements. These include, among others, functional efficiency, economic feasibility, and IEQ. Commonly, both formulations of quality requirements (e.g., in terms of codes, standards, guidelines) and methods for their evaluation (e.g., code compliance methods and certification procedures) are organized along such aspects. The IEQ aspect, which is the focus of the present discussion, directly relates to user needs. The overarching objective of the specification and evaluation of IEQ-related performance criteria is presumably the provision of conditions that are conducive to building inhabitants' health, comfort, and well-being. Consequently, the formulation of IEQ requirements must be based on the knowledge of the effects of relevant indoor-environmental conditions on human health, comfort, and well-being.

However, the operationalization of such high-level concepts is rather non-trivial, given their arguably imprecise and at times overlapping definitions. For instance, health is frequently defined as "the state of being free from illness or injury", comfort as "a state of physical ease and freedom from pain or constraint", and well-being as "the state of being comfortable, healthy, or happy" [3]. A number of these attributes are included in WHO's definition of health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [4].

These observations provide a conceptual basis for the understanding of conventional approaches toward formulation of IEQ standards. The basic function of current standardization practices in this area appears to involve the following ingredients:

- A number of measurable (typically physical) indicators of indoor-environmental conditions (e.g., air temperature, humidity, illuminance, sound level) are assumed to be pertinent independent variables in view of environmental quality specification.
- These variables are mapped into another set of (in this case dependent) variables that are treated as indicative of human health, comfort, and well-being (e.g., thermal comfort, visual comfort).
- The logic of mapping operations is frequently based on a mix of causal (typically physiological) and data-driven (typically correlational) models.
- The mapping operations and the resulting rules of inference are structured in terms of multiple distinct clusters.
- These clusters follow loosely (not strictly) the typology of human sensory channels, i.e., haptic (relevant in view of thermal perception), visual, auditory, and olfactory (relevant in view of indoor air quality perception) senses.

The majority of conventional IEQ standards can be said to be mono-dimensional. In other words, the mapping of indoor-environmental variables to respective high-level indicators of health, comfort, and well-being is typically conducted in an isolated fashion for a distinct cluster, that is, one of the above-mentioned sensory modes, even though several distinct clusters may be included under the umbrella of a single standard. But this does not mean that there have been no efforts to develop and promote methods and procedures for multi-domain building quality evaluation and certification, which also include interactions between individual domains. However, before embarking on a closer inspection of a number of such methods, it may be useful to briefly reflect upon the related option space via a kind of logical analysis.

Consider the case of codes, standards, or guidelines that are meant to support decision making relevant to the design and operation of indoor environments. Generally speaking, such documents may be based on three approaches or strategies:

i. The first strategy—commonly deployed in the majority of current evaluation schemes—involves the categorization of requirements into distinct sets pertaining to separate domains (e.g., thermal, visual, acoustic). In this case, the evaluation is conducted (and the evidence of compliance is provided) separately for each domain.
ii. The second strategy aims to subsume multiple quality evaluation domains in a unitary—typically point-based or credit-based—framework. Thereby, an overarching or total quality score is derived based on the combination (e.g., simple or weighted addition) of individual domains' scores. The strategy could also include additional features, such as requiring a mandatory minimum score for each domain as a condition of certification.
iii. The third strategy would pursue a truly integrative path. Thereby, inherent—physiologically or psychologically relevant—interactions, independencies, and cross-effects among various influencing variables in different perceptual dimensions would be taken into consideration, including their complexity and presumptive non-linearity.

As alluded to before, the primary purpose of the present discussion is to obtain a general view of the state of art in view of multi-domain approaches to evaluation and certification of IEQ. Consequently, we consider a number of existing methods and procedures in this area. Specifically, we explore the extent to which the options (ii) and (iii) above have been actually realized. Note that the intention is not to provide an exhaustive review of all relevant documents, but to focus on a number of common instances that may be considered to be typical. The related investigation is expected to deepen insights regarding the necessary conditions for future integrative methods and procedures for the evaluation of buildings' IEQ.

3. Existing Instances of Multi-Domain Building Quality Evaluation Approaches

3.1. Introductory Remark

It was mentioned already that the perceived need for integrated approaches to building quality certification in general and IEQ evaluation in particular has led to the introduction and application of a number of national and international schemes. In this section, we provide a few instances of such schemes. Needless to say, we shall not engage in discussion of the myriads of codes, standards, and other evaluation systems that are predominantly single-domain (see, for instance, EN 12464-1 [5]). Nor shall we make an attempt to include every instance of an evaluation scheme that addresses more than one domain. As alluded to before, our objective here is not to conduct an exhaustive review. Rather, the intention is to consider a selected number of schemes that may be suggested to entail the generic features of most existing multi-domain approaches to building quality evaluation. Aside from providing some basic information about the selected schemes, they are examined with regard to the following questions:

- What is the overall spectrum of building quality aspects these schemes cover?
- Which of the covered aspects are directly relevant to IEQ considerations?
- What indicators are used as proxies of IEQ?
- How is the integration challenge addressed, i.e., what method is used to integrate multiple domains into a holistic/unified quality indicator?

3.2. The Selected Instances

For the discussion in this paper, we considered a variety of different schemes, guidelines, and standards. Note that the purpose of this inquiry was not an exhaustive review of all instances of rating systems applied around the world. Such an effort would have been neither productive nor necessary, as, for instance, a number of rating systems appear in multiple slightly modified versions to account for certain nationally or locally relevant adjustments but use the same overall evaluation methods. The selection process benefited from the involvement of and input from an international group of experts engaged in the collaborative framework of the International Energy Agency (IEA), Energy in Buildings and Communities (EBC) Programme [6]. An ongoing Annex in this platform (Annex 79: "Occupant-Centric Building Design and Operation") [7] that involves some 140 international experts, explicitly addresses knowledge and methods required for occupant-responsive building design and operation. Specifically, the experts in the Subtask 1 of this Annex ("Multi-aspect environmental exposure, building interfaces, and human behaviour") engage in an in-depth assessment process of existing state and future needs concerning occupant-centric multi-domain evaluation methods of buildings' indoor environments. The selection of the evaluation and certification schemes for the present paper benefited from an iterative input acquisition process. Consequently, a number of system instances could be identified, which—while not including all pertinent schemes—could be suggested to capture main strategies and approaches adapted toward multi-aspect building quality assessments. The inclusion of the instances was conditional to positive answers to the following questions: Are the candidate schemes applied in professional practice and/or considered in academic discourse? Do the candidate schemes explicitly address multiple quality aspects and domains? Do the candidate schemes suggest some form of evaluative integration strategy?

Table 1 provides an overview of the selected schemes. The final selection includes three sustainability rating schemes: DGNB [8] of the German Sustainable Building Council, LEED (Leadership in Energy and Environmental Design) [9] of the U.S. Green Building Council, and Miljöbyggnad [10] of the Sweden Green Building Council. WELL Building Standard [11] was selected mainly due to its expressed occupant-centric orientation in view of a wider spectrum of factors that are relevant to people's well-being and health. ASHRAE Guideline 10 [12] is an interesting case as it explicitly addresses interactions between the IEQ domains. Finally, EN 15232 [13] aims at supporting the development of an automation concept and therefore targets IEQ domains during building operation. It is conceivable that one or the other instance in the above selection could be replaced by another scheme. However, given the family resemblances with the items in the selected set, we expect that this would not be tangential on the subsequent treatment and the conclusions of the present contribution.

Table 1. Overview of selected schemes [8–13].

Scheme	Domain					Method of Aggregation/ Integration
	Thermal	Visual	Acoustic	IEQ	Other	
DGNB	X	X	X	X	User control as IEQ domain, more domains in socio-cultural aspect, other quality aspects: environmental, economic, technical, site	Points and weighting factors based
LEED	X	X	X	X	Energy, materials, water, pollution, transport	Points based
Miljö-byggnad	X	X	X	X	Energy, material, and chemical	Points based
WELL	X	X	X	X	Mental health, well-being	Points based
ASHRAE Guide 10	X	X	X	X	None (Personal control, adaptation, and others only mentioned introductory as potential environmental components affecting human responses)	Qualitatively, based on research results, no quantification
EN 15232	X	X		X	Energy, addressing building automation concept and domain's indicator control	None

3.3. The DGNB Certification

3.3.1. Background and Objectives

The DGNB ("Deutsche Gesellschaft für Nachhaltiges Bauen": German Sustainable Building Council) is a non-profit organization, founded in 2007 and based in Stuttgart, Germany [14]. Its stated aim is to address the quality, responsibility, and sustainability in buildings and urban districts. Toward this end, the DGNB developed its own certification system, called DGNB System [8], which was released in 2009 and has been modified since then. The DGNB certification system is meant to offer adaptation possibility for international application, e.g., the Danish DGNB system. Hence, local organizations could adjust it to specific conditions and legal requirements.

3.3.2. Quality Aspects, IEQ-Relevant Domains and Indicators

The DGNB System aims to address the overall performance of building-related projects throughout their entire life cycle. Thereby, ecological, economical, and sociocultural dimensions of sustainability are considered. The system is available for application at multiple scales (whole buildings, building interiors, entire districts). Six building quality aspects are defined, namely, environmental, economic, socio-cultural and functional, technical, process, and site quality. These were adjusted for new buildings, building retrofit measures, and building operation applications. Table 2 provides an overview of the aforementioned six quality aspects as well as the specific share of each aspect (in percentage terms) in the total evaluation. The information in this table specifically applies to new construction projects. For other applications (i.e., those pertaining to existing buildings and building operation scenarios), the number of considered categories and the selected metrics may differ. However, the overall logic of the evaluation strategy is very similar. Note that, for certain quality aspects, the listed share in the total score varies. This is due to the consideration of building types in the DGNB system. As such, the system distinguishes the following building types: Office (O), Educational (E), Hotel (H), Residential (R), Consumer market (C), Shopping center (S), Department stores (D), Logistics (L), and Production (P).

Table 2. Evaluation quality aspects of the DGNB ("Deutsche Gesellschaft für Nachhaltiges Bauen": German Sustainable Building Council) system together with the subject of evaluation [15], respective domains of each aspect, as well as each aspect's share in the overall evaluation.

Building Quality Aspect	Subject of Evaluation	Constitutive Domains	Share of Total Score [%]
Environmental	"effects of buildings on the global and local environment as well as the impact on the resources and the generation of waste"	i. building life cycle assessment; ii. local environmental impact; iii. sustainable resource extraction; iv. potable water demand and wastewater volume; v. land use; vi. biodiversity at the site	22.6
Economic	"long-term economic viability (life cycle costs) and economic development"	i. life cycle cost; ii. flexibility and adaptability; iii. commercial viability	22.5
Sociocultural and functional	"health, comfort and user satisfaction as well as the essential aspects of functionality"	i. thermal comfort; ii. indoor air quality; iii. acoustic comfort; iv. visual comfort; v. user control; vi. quality of indoor and outdoor spaces; vii. safety and security; viii. design for all	25.6–32.2
Technical	"technical quality in a view of relevant sustainability aspects"	i. fire safety; ii. sound insulation; iii. quality of the building envelope; iv. use and integration of building technology; v. ease of cleaning building components; vi. ease of recovery and recycling; vii. emissions control; viii. mobility infrastructure	17.7–17.8
Process	"planning quality and the construction quality assurance"	i. comprehensive project brief; ii. sustainability aspects in tender phase; iii. documentation for sustainable management; iv. procedure for urban and design planning; v. construction site/construction process; vi. quality assurance of the construction; vii. systematic commissioning; viii. user communication; ix. FM-compliant planning	12.3
Site	"impact of the project on its environment and vice versa"	i. local environment; ii. influence on the district; iii. transport access; iv. access to amenities	5.0

Given the specific orientation of the present paper, we focus in the following on those DGNB system features that are directly relevant to IEQ aspects. These are listed, in this system, as part of the

"Sociocultural and functional quality" aspect, which comprises eight domains. Thereby, five domains are directly relevant to IEQ, namely, thermal comfort, visual comfort, acoustic comfort, indoor air quality (IAQ), and user control. For each of these domains, a number of pertinent indicators are identified, to be considered in the evaluation process. Moreover, the DGNB system documentation lists relevant references (typically national or international codes and standards) to be consulted for the details on the indicators. Table 3 provides an overview of the IEQ-related domains, the corresponding indicators, and the related references. Note that the provided references apply to specific building types. Furthermore, the table does not explicitly include information on points that can be obtained via so-called bonus options [16–18].

Table 3. Overview of the indoor environmental quality (IEQ)-related domains in the DGNB system together with the corresponding indicators and the related information including references (abbreviations for building functions in this table are as follows: Office (O), Educational (E), Hotel (H), Residential (R), Consumer market (C), Shopping center (S), Department stores (D), Logistics (L), and Production (P)).

Domain	Indicators	Related References
Thermal comfort	Operative temperature; indoor air temperature (heating period)	EN 15251 [19] for O, E, R, C, H, L, PASR A3.5 [20] for L, P
	Draft (heating and cooling periods)	ISO 7730 [21] for O, E, R, H, C, L, P
	Radiant temperature asymmetry and floor temperature (heating and cooling periods)	Minimum and maximum values are set in °C for O, E, R, H, L, P [16]
	Relative humidity (heating period)	$\phi \geq 25\%$ for O, E, R, L, P, C, S;$75\% \geq \phi \geq 25\%$ for H (EN 15251 [19])
	Operative temperature, indoor air temperature (summer period)	National criteria or MIN_FAC [16] (whichever is stricter) andEN 15251 [19] for O, E, R, H, C, S, D, L, PDIN 4108-2 [22] for O, E, R, H, C, D, L, PASR A3.5 [20] for L, P
	Relative humidity (cooling period)	Absolute humidity < 12 $g \cdot kg^{-1}$ for O, E, R, H, L, P, C, S (EN 15251 [19])
IAQ	Volatile Organic Compounds	ISO 16000-3 [23], ISO 16000-6 [24] or EPA/625/R-96/010b [25–28] or ANSI/ASHRAE/USGBC/IES Standard 189.1-2014 [29] or National regulation for O, E, H, R, L, P;DGNB ENV1.2 [30] for S, D, L, P
	Ventilation rate	EN 15251 [19] for O, E, H, S, D, CDIN 1946-6 [31] for RASR A3.6 [32] for L, P
Acoustic comfort	Room acoustics concept	Creation of room acoustics concept plan, updating it during the planning process [18]
	Reverberation time T_{target}	DIN 18041 [33] for O, E, H
	A/V ratio in the frequency range 250–2000 Hz	DIN 18041 [33] for O, E, H
Visual comfort	Availability of daylight for the entire building	Prescribed values for the daylight factor (DF) in relation to the usable area (UA) for O, E, R, H, C, S, D, P [34]
	Availability of daylight at permanent workstations	Percentage values are prescribed for O, E, L [34]
	Visual contact with the outside	Prescribed requirements for S, D, C, O, E, H, L, R [34]

Table 3. *Cont.*

Domain	Indicators	Related References
	Absence of glare in daylight	EN 14501 [35] for O, E;ASR A3.4 [36] for C;Prescribed requirements for P [34]
	Artificial lighting	EN 12464-1 [5] for O, E, H, C, D, S, L, P
	Color rendering index Ra	Prescribed values for Ra for O, E, P, R, H, L, S [34]
	Duration for exposure to daylight	Prescribed values in [h] are set for a minimum percentage of the living spaces for R, H [34]
User control	Ventilation control	Prescribed rates for O, E, R, C, S, D, H [37]
	Shading and glare protection control	Prescribed values for O, E, H [37]
	Room temperature control (during and outside of the heat period)	Prescribed values for O, E, R, C, S, D, H [37]
	Artificial light control	Prescribed values for O, E, H [37]

3.3.3. Evaluation Method and Weighting Factors

The integration of multiple evaluation aspects in the DGNB certification systems works on the basis of defining the share of each domain in the total score as a function of the building type. The evaluation scheme used in the DGNB system is based on the assignment of points on indicator level. The aggregation to an overall assessment uses weighting factors or credits. Depending on the achieved percentage of the applicable maximum points, a project can obtain one of the labels, namely, Platinum (≥80%), Gold (≥65%), Silver (≥50%), and Bronze (≥35%, relevant only to existing buildings and building operation applications). Table 4 summarizes the share of the five IEQ-related evaluation domains (individually and in total) in the final score as a function of building type. It also includes the shares of the other domains in the aspect “sociocultural and functional quality”.

3.4. LEED

3.4.1. Background and Objectives

The US Green Building Council was formed in 1993 to foster the development and the transformation of the construction sector into a more sustainable market for improving the quality of life toward environmental sustainability and social responsibility. The first “ready to use” protocol LEED v1.0 was officially launched on 1998 with 19 pilot sites for testing purposes. From the very beginning, the following environmental quality domains were considered: (i) energy efficiency, (ii) water saving, (iii) maintenance cost sustainability, (iv) overall better indoor and outdoor environmental quality and multidomain comfort for occupants, and (v) reduced impact on the pertinent sites. In the subsequent years further new and specific versions of the protocol have been developed for extended markets including LEED for Existing Buildings, LEED for Commercial Interiors, and LEED for Core and Shell.

LEED v2009 introduced the first weighting factors based on the Environmental Protection Agency’s TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) and the National Institute of Standards. This evolution meant the transition from a general framework into a specific credit-based protocol for informing and monitoring the design and construction process toward wellbeing, energy efficiency, and environmental sustainability. The current versions LEED 4 [38] and LEED 4.1 [39] include upgrades toward better implementation of the performance-based approach and increased attention to the use of resources (materials and water). Related dedicated categories address the life cycle of deployed materials in LEED certified buildings. A new LEED compliant protocol has been recently developed in Italy, to be soon translated into an international standard. It consists of Green Building Council Italia (GBCI) for Historic Buildings, and it includes new categories for preservation of the historical heritage in the built environment.

Table 4. Overview of the share of each evaluation domain (in percentage) of the total score in the DGNB system (new buildings) as a function of building type. Included are the total shares for IEQ-related domains as well as the total share for the sociocultural and functional quality aspect.

		Building Type								
		Office	**Educational**	**Hotel**	**Residential**	**ConsumerMarket**	**ShoppingCentre**	**DepartmentStores**	**Logistics**	**Production**
IEQ domain	Thermal comfort	4.1	3.6	3.9	4.3	4.5	4.5	4.5	4.3	4.3
	Indoor air quality	5.1	4.5	4.9	5.4	4.5	4.5	4.5	5.4	5.4
	Acoustic comfort	2.0	2.7	2.9	0.0	0.0	0.0	0.0	0.0	0.0
	Visual comfort	3.1	2.7	2.0	3.2	3.4	3.4	3.4	3.2	3.2
	User control	2.0	1.8	2.0	2.1	2.3	2.3	2.3	0.0	0.0
Total for IEQ		16.3	15.3	15.7	15.0	14.7	14.7	14.7	12.9	12.9
Other domains	Quality of indoor and outdoor spaces	2.0	1.8	2.0	2.1	2.3	2.3	2.3	5.4	5.4
	Safety and security	1.0	1.8	2.0	1.1	1.1	1.1	1.1	4.3	4.3
	Design for all	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	9.6
Total for sociocultural and functional quality		26.8	26.4	27.2	25.7	25.6	25.6	25.6	30.1	32.2

3.4.2. Quality Aspects, IEQ-Relevant Domains and Indicators

A variety of protocols were developed and implemented. Each protocol is meant to be a specific rating system with a set of consistent quality aspects, but with different weighting factors for each indicator, referred to as "credit". The different protocols include the following:

- Building Design and Construction: including New Construction and Core and Shell, which may be applied to schools, retail buildings, hotels, data centers, warehouses and distribution centers.
- Interior Design and Construction: aimed at the interior design of commercial spaces.
- Building Operations and Maintenance: aimed at certifying existing building renovations.
- Neighborhood Development: aimed at large developments or redevelopment projects of residential and non-residential communities.
- Homes: aimed at single family houses and multifamily low-rise and mid-rise houses up to six-story buildings.
- Cities and Communities: aimed at entire neighborhoods and cities including a focus on transportation quality.
- LEED Recertification: guides the maintenance and potential improvement of the sustainability approach in existing and already occupied and certified buildings.
- LEED Zero: helps already certified projects (under the protocols for new constructions and major renovations) to meet zero-impact targets (zero-energy use, zero-carbon emissions, and zero-resources).

The certification quality aspects are displayed in Table 5.

Table 5. Evaluation quality aspect of the LEED certification, respective categories in each aspect, as well as each aspects' share in the overall evaluation. The key to the enumeration of the category items is as follows: (a) building life cycle assessment; (b) local environmental impact; (c) sustainable resource extraction; (d) potable water demand and waste water volume; (e) land use; (f) site biodiversity; (g) air and ground pollution; (h) energy efficiency and green energy.

Building Quality Aspect	Subject of Evaluation and Objectives	Categories	Maximum Points
Location and transportation	Site development, aimed at minimizing transportation impact of dwellers and employees and to improve human health by fostering physical activity (bicycle facilities) and walking distances.	a, b, c, d, e, f	20
Sustainable Sites	Minimization of air and light pollution generated by the construction activities and to reduce soil erosion, airborne dust, and waterway sedimentation. It also includes preservation of green fields to reduce water runoff and mitigate urban heat island. Promotion of open spaces for greenery and encouragement for social interaction and physical activities.	a, b, c, d, e, f, g	15
Water Efficiency	Mandated water waste reduction for both indoor and outdoor irrigation, including the installation of metering systems to support the water system operation and management.	a, b, c, d	15
Energy and Atmosphere	Energy efficiency improvement and integration with renewables. Green energy contracts and advanced simulation tools are encouraged for a better understanding of the dynamic performance of the building. An upper limit to renewable energy deployment is set, in order to avoid the excessive deployment of low-performance renewable energy components.	a, b, c, h	35
Materials and Resources	Fostering re-use and recycling of building materials and the use of sustainable low-emission materials (low emitting materials) from the proximity of the construction site.	a, b, c, d, e, f	20
Indoor Environmental Quality	Multi-domain indoor well-being assessment aimed also at productivity of building occupants.		20
Innovation	Fostering implementation of innovative solutions or exceptional performance practices. Periodical assessment and protocol upgrade toward inclusion of innovations into practice, i.e., as credits in the future protocol versions.		5
Regional Priority	Addressing regional considerations, including environmental quality, social equity, and public health priorities.		4

LEED protocols involve dedicated IEQ domains with three prerequisites regarding (i) air quality minimum performance, (ii) tobacco smoke control, and (iii) acoustic minimum performance requirement. Table 6 provides an overview of LEED IEQ domains.

Table 6. Overview of the IEQ-related domains in the LEED protocols together with the corresponding indicators and the related information including references.

Domain	Indicators: Prerequisites and Credits	Related References
Indoor air quality	Prerequisite 1: minimum indoor air quality performance	ASHRAE Standard 62.1–2010 [40];CEN Standards EN 15251–2007 [41] and EN 13779–2007 [42]
	Prerequisite 2: environmental tobacco smoke control	Smoking not permitted or permitted only at a mandated from openings.
	Prerequisite 3: minimum acoustic performance	ANSI Standard S12.60–2010 [43]; 2011 HVAC Applications ASHRAE Handbook, Chapter 48, Noise and Vibration Control [44]; AHRI Standard 885–2008 [45]
	Credit: enhanced indoor air quality strategies	ASHRAE Standard 52.2–2007 [46]; CEN Standard EN 779–2002 [47]; CIBSE Applications Manual 13–2000 [48]; ASHRAE 62.1–2010 [40]
	Credit: low-emitting materials	CDPH Standard Method v1.1; ISO 16000-3: 2011 [49], ISO 16000-6: 2011 [50], ISO 16000-9: 2006 [51], ISO 16000-11:2006 [52] and national standards
	Credit: construction indoor air quality management plan	ASHRAE 52.2–2007 [46]; CEN Standard EN 779–2002 [47]
	Credit: indoor air quality assessment	ASTM and US EPA methods, and ISO methods
Thermal comfort	Credit: thermal comfort	ASHRAE Standard 55–2010 [53], ISO 7730:2005 [54], CEN Standard EN 15251:2007 [19]
Acoustics	Prerequisite: minimum acoustic performance	ANSI Standard S12.60–2010 [43]; 2011 HVAC Applications ASHRAE Handbook, Chapter 48, Noise and Vibration Control (with errata) [44]; AHRI Standard 885–2008 [45]
	Credit: acoustic performance	2011 ASHRAE Handbook [55]; AHRI Standard 885- 2008 [45]; ANSI S12.60–2010 Part 1 [43], or local equivalent
Lighting	Credit: interior lighting	Specific requirements regarding lighting control and lighting quality, differentiated by building use and related protocol.
	Credit: daylight	Specific requirements concerning daylight autonomy, to be calculated via simulation, differentiated by building use and related protocol.
	Credit: quality view	Specific requirements concerning direct line of sight to the outdoors.

The first prerequisite related to air quality refers to ASHRAE 62.1-2010 Standards [40] or CEN Standards EN 15251-2007 [19] and EN 13779-2007 [42], in case of mechanically ventilated buildings.

In naturally ventilated buildings, the protocol refers only to ASHRAE 62.1 Standard [40]. Air quality has to be also continuously monitored in terms of air changes per hour or CO_2 concentration in each thermal zone, for naturally ventilated zones. The third prerequisite—only applied to school buildings—concerns acoustic environmental quality control for enhancing teaching and communication. The "Enhanced indoor air quality strategies" dedicated credit covers up to 2 points in all the protocols and promotes occupant comfort, well-being, and productivity. The proposed ventilation strategies aim at preventing cross-contamination and inform the respective calculation procedures for the professionals.

The credit "Low-Emitting Materials" accounts for up to 3 points in all protocols. It aims at reducing the concentration of chemical polluting agents. Specific assessment involves VOC content estimation due to coatings, wood-based materials, binders, and sealants. Another point is assigned to the credit "Construction Indoor Air Quality Management Plan", which fosters the development of a dedicated plan for better managing occupants' well-being and productivity. The focus hereby is on particulate matters and moisture but also on outdoor emissions (particularly in healthcare buildings). The "Indoor Air Quality Assessment" accounts for up to 2 points. It aims at the periodic assessment of air quality and recommends a flush out prior to occupancy. Measurements under standard conditions (air testing) represent an alternative assessment option.

The "Thermal Comfort" credit accounts only for 1 point. The control option recommends to provide the single-occupancy thermal zones with individual thermal comfort control options for at least 50% of spaces, and group controls in multi-occupant spaces. Control interfaces should allow for the regulation of at least one of the following parameters: air temperature, radiant temperature, air speed, and relative humidity. Specific requirements apply to patient rooms in healthcare buildings.

The "Interior lighting" credit accounts for up to 2 points. Here, the credit is achieved if occupants can easily and individually control the lighting conditions (more than 90% of individual controls in individually occupied areas) in terms of at least three levels (on, off, and default). Attention is also to be paid to glare risk, high CRI (Color Rendering Index) lighting systems, and long-life cycle for lighting systems.

"Daylight" credit accounts for up to 3 points in order to promote the connection with the outdoors, enhance the circadian rhythm, and reduce artificial lighting use. Daylight autonomy has to be dynamically simulated to both optimize spatial autonomy and reduce direct sunlight exposure. Illuminance calculations need to demonstrate the provision of specified illuminance levels (at specific times and under specified sky conditions) for more than 75% (1 point) or 90% (2 points) of the floor area. The "Quality Views" credit requires occupant visual connection to outdoors in more than 75% of regularly occupied spaces. It accounts for up to 2 points.

"Acoustic performance" accounts for up to 2 points. It applies only to new constructions (schools, data centers, warehouses, hotels, and healthcare buildings). Here, the credit includes HVAC noise measurement. It also wants the building to maintain STC (Sound Transmission Class) rating for adjacent spaces of 55 in residential spaces up to 60 in mechanical equipment rooms. Further requirements are specified for reverberation time and speech transmission index.

3.4.3. Evaluation Method and Weighting Factors

LEED certification is achieved through earning points in several categories, each one characterized by relative credits (accounting for one or more points). By summing up all the achieved points, four rating levels may be awarded: Platinum (80 and more points), Gold (60 to 79 points), Silver (50 to 59 points), Certified (40 to 49 points). Another key point of the LEED rating system is the differentiation between prerequisites and credits. While credits may account for 1 or more points and are not mandated, prerequisites in each category are. Even if only one prerequisite is not fulfilled, the whole LEED certification cannot be awarded.

Concerning the IEQ assessment, LEED protocols cover thermal, lighting, acoustic, and air quality aspects, with a total weight of 20 points maximum, which is comparable to the weight given to other aspects of the LEED protocols.

Protocols include both physical (e.g., specific IAQ-related measurements) and non-physical (e.g., outdoor view quality) considerations. IAQ and acoustic comfort are given more attention in LEED as compared to thermal comfort (which only accounts for 1 point). However, in the LEED scheme, the comfort, well-being, and productivity are always mentioned together, which is meant to underline the occupant-centric focus of the protocol.

3.5. Miljöbyggnad

3.5.1. Background and Objectives

Miljöbyggnad (in English: Environmental Building) is a Swedish system for environmental certification of buildings. Miljöbyggnad is administered and awarded by the Sweden Green Building Council. It was collaboratively developed by the municipalities, researchers, and companies in the construction and property sectors [10]. In 2003, the development of the Miljöbyggnad was initiated by the Swedish government in the Bygga-bo-dialogen (build-live-dialogue) to be able to meet the growing demand for environmental certification in the building sector. It was developed as a relatively simple and cost-effective tool to assess environmental impact and sustainability for both newly constructed and existing buildings. In 2010, the first two Miljöbyggnad buildings were certified in Sweden. The overarching goal of Miljöbyggnad is the provision of adequate and safe environments for people to work and live in. The major focus is on environmental and social sustainability [56].

3.5.2. Quality Aspects, IEQ-Relevant Domains and Indicators

Miljöbyggnad is relevant to new constructions and reconstruction and extension of existing buildings. It covers most building typologies (houses, apartment buildings, offices, schools, commercial premises, etc.) The certification is based on the Swedish building regulation BBR [57] and is applicable to most projects in Sweden. It certifies buildings with regard to energy, indoor environment, and materials/chemicals. The energy aspect aims to reduce building energy use and to achieve building low carbon dioxide emissions by using renewable energy. The aspect of indoor environment strives for comfortable and healthy conditions for occupants while considering multiple domains. The materials and chemicals aspect aims to prevent from using building materials containing hazardous substances with negative environmental impact [58].

The newest version of Miljöbyggnad 3.1, includes, under the aforementioned three aspects, 13 domains and a total of sixteen indicators. The indoor environment aspect contains six main domains, namely, noise, indoor air quality (ventilation rate, radon concentration), thermal comfort (thermal conditions in winter and summer), daylight, moisture, and legionella. Detailed performance indicators for four of the IEQ domains are summarized in Table 7 [59].

Table 7. Indicators of IEQ domains in Miljöbyggnad certification.

Domain	**Indicators**
Noise	Sound pressure level; reverberation time; weighted apparent sound reduction index; impact sound pressure level; sound level difference
Indoor air quality	Ventilation rate; carbon dioxide concentration; radon content; gamma radiation level
Thermal comfort	Predicted Percentage of Dissatisfied (PPD); air velocity; window area to floor area (TF)
Daylight	Daylight factor (DF); window glazing area to floor area (AF)

The inclusion of specific indicators in the certification process depends on the nature of the projects (i.e., new construction, building retrofit) and the building typologies (e.g., residential, commercial).

In parallel, in view of applicable tools to query occupants' perception of indoor environment (indoor climate, IAQ, acoustics), Miljöbyggnad also includes surveys as an alternative to measurements.

3.5.3. Evaluation Method

Miljöbyggnad certifies buildings at three levels, namely Bronze, Silver, and Gold. These are related to requirements of Swedish building regulation BBR [57]. Bronze refers to the buildings that comply with the legal requirement of BBR, such as building energy use and indoor radon content. Silver is awarded when a building performs better than the reference values in BBR (e.g., higher daylight factor, lower PPD value). Gold certification is the highest rating in Miljöbyggnad system with higher target values. For example, for new buildings, daylight factor is increased from 0.8% at Bronze level to 1.3% at Gold level; acoustically relevant parameters need to conform to noise class B, and energy use cannot be higher than 30% of BBR's set value at Gold level. Moreover, occupants' perception is addressed to the Miljöbyggnad ranking. As such, Gold level attaches importance to occupants' experience. Specifically, survey as an alternative to measurement in the Gold ranking requires that at least 80% of the occupants state that they find the actual environment in view of thermal comfort, acoustics, and ventilation very good, good, or acceptable.

The rating method of Miljöbyggnad certification is based on a combination and aggregation of the indicators, domains, and aspects [10]. The aggregation process is conducted in terms of four steps, i.e., from indicator, to domain, to aspect, to building. The lowest indicator rating determines the domain rating, and the lowest domain determines the aspect rating. The lowest aspect rating determines the building rating. Thus, in practice, if a Gold certification is to be achieved, most of the indicators must have a Gold label and none can be Bronze.

3.6. WELL Building Standard and Certification

3.6.1. Background and Objectives

WELL was introduced in 2014 by the International WELL Building Institute (IWBI) with a specific focus on building occupants' "health and wellness" [11]. In 2018, the second version was launched as a pilot. The main principles of WELL aim toward an adaptable and robust methodology and certification scheme that is meant to be based on technical evidence and objective, measurable indicators.

3.6.2. Quality Aspects, IEQ Relevant Domains, and Indicators and Ranking Methodology

In the context of the generic approaches of the standards as described in Section 2 of this paper, WELL belongs to the point-based frameworks and is structured around ten "concepts" (quality aspects): Air, Water, Nourishment, Light, Movement, Thermal Comfort, Sound, Materials, Mind, and Community. Each concept has a number of mandatory "preconditions" and a selection of "optimizations" that provide a number of points, whereby there is a cap of points for each concept (Table 8). The points are aggregated to calculate the total points with a minimum of 2 points per concept and maximum of 100 + 10 points (10 additional points for innovation) to each project. The point value of the different optimizations reflects the positive or negative impact of each feature on the health and wellness of occupants and the possible effect of any interventions [11]. The preconditions and optimizations available for each concept apply to different spaces within a building. It is implied that there shall be a verification process based on, among others, on-site assessments, performance testing, review of policy documentation, photographic evidence, on-going data reporting, modelling, and architectural drawings.

Table 8. The distribution of preconditions, optimizations, and the available points, respectively, for each quality aspect (concept) of the WELL v2 standard.

WELL Concept—Quality Aspect	Preconditions	Optimizations	Total Points
Air	4	10	18
Water	3	6	10
Nourishment	2	11	17
Light	2	6	14
Movement	2	10	20
Thermal comfort	1	6	12
Sound	1	5	13
Materials	3	11	22
Mind	2	13	24
Community	3	14	33
Innovations	-	5	18

3.6.3. Comfort Related Domains and Integration with Other Standards

In relation to the multiple domains of IEQ, the framework assesses the indoor air quality, ventilation efficiency, lighting design and light exposure, physical activity and ergonomics, thermal comfort, noise levels, and acoustical disturbance. Moreover, weighted points are also given for glare control, operable windows, electric light quality and control, individual thermal comfort, humidity control, and noise management. In addition to these domains, the framework includes construction materials and water quality. There are a number of concepts included that are more focused on health and well-being such as mental health, nourishment options, workplace health, and community development. Table 9 includes a listing of the main indicators in each domain relevant to IEQ. Note that the listed points in this table do not add up to the total available points, as indicators not directly related to IEQ are not included.

Table 9. Overview of the IEQ related domains and key indicators per relevant quality aspect (concept) assessed by the WELL v2 framework.

Quality Aspect	IEQ Domain	IEQ Indicator (Weighting)
Air	IAQ	- Air quality (4/18) - Ventilation (3/18) - Operable windows (2/18) - Monitoring and awareness (2/18) - Mold control (2/18)
Water	Moisture management	- Moisture management (3/10)
Light	Visual	- Circadian lighting design (3/14) - Glare control (3/14) - Daylight access (3/14) - Electric light quality (2/14) - Occupant control of lighting (2/14)
Movement	Activity/circulation	- Movement network (3/20) - Enhanced ergonomics (1/20)

Table 9. *Cont.*

Quality Aspect	IEQ Domain	IEQ Indicator (Weighting)
Thermal comfort	Thermal	- Enhanced thermal comfort (3/12) - Individual thermal control (3/12) - Radiant thermal comfort (2/12) - Thermal comfort monitoring (1/12) - Humidity control (1/12)
Sound	Acoustic	- Max noise levels (3/13) - Impact noise management (2/13)
Materials	IAQ	- VOC reduction (3/22) - Long-Term emission control (3/22) - Short-Term emission control (3/22)
Community	IAQ	- Enhanced occupant survey (2/33)

It is assumed that, in many countries, several preconditions would be met via compliance with the national building codes and regulations. To achieve WELL targets, often thresholds and limits from documents such as ASHRAE standards, ISO, EN, or the UK CIBSE Guides apply. However, it is also possible to certify other national building regulations as equivalent to the recommended standards. In addition, the technical requirements and procedures for testing and verification are set out in a guidebook for assessors to ensure that the same procedures are followed for the evaluation of different projects around the world. As such, WELL relies on recognized international standards and codes to incentivize the use of existing solutions and support continuous evaluation and post-commission monitoring.

3.7. ASHRAE Guideline 10-2016

3.7.1. Background and Objectives

ASHRAE Guideline 10 was first published in January 2011. Its most recent version was published in January 2016 [12]. This guideline, published by the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers), was developed by the ASHRAE Standing Guideline Project Committee 10 including experts from research and practice. The purpose of this guideline is the provision of guidance regarding IEQ factors and their interaction with regard to comfort and health. In contrast to the schemes discussed above, ASHRAE Guideline 10 sets target ranges or values for acceptable indoor environmental conditions neither for individual IEQ indicators nor for their combinations. As such, it aims at raising awareness rather than prescribing ranges or values, reflecting the available literature at time of publication. Accordingly, the guideline consequently refers to scientific literature and includes in total 87 references to original scientific work and 13 references to other standards.

3.7.2. Quality Aspects, IEQ-Relevant Domains and Indicators

ASHRAE Guideline 10 focusses on IEQ-related domains including thermal, IAQ, illumination (electric and daylight), and acoustics (sound and vibration). Metrics or performance ranges are given neither for individual IEQ indicators nor for their interactions. The guideline introduces the four domains individually together with an introduction of overall acceptability. Regarding the relationship between the average scores of individual aspects to the overall acceptability, a single source is cited [60]. Table 10 gives an overview of IEQ domains and corresponding indicators. This is followed by a brief introduction of human adaptability and its limitations as well as a section on the interaction between human physiological and psychological response, which includes the concept of personal control.

Table 10. IEQ domain and IEQ indicators.

IEQ Domain	Indicator
Thermal	PMV index Temperature Clothing Metabolism Humidity Heating equipment
IAQ	Perception of air quality (including sense of smell, perception of chemical components of air, perception of odor intensity, freshness of air, stuffiness, and acceptability) VOC, formaldehyde, particulate matter, particle deposition (e.g., on computer screens), ozone, biological contaminants, odor Pollutants from indoor sources (e.g., occupants, building materials) and outdoor sources (e.g., combustion products)
Visual	Source of lighting (daylight or electric lighting) Illumination
Acoustic	Sound Vibration Sound from ventilation equipment

A valuable source for future multi-domain IEQ standards can be seen in the definitions of the types of interactions referred to as additive, synergistic, antagonistic, prophylactic, cumulative, and unintended.

3.7.3. Evaluation Method and Consideration of Interactions

The main part of ASHRAE Guideline 10 focuses on interactions. Given its in general descriptive structure, the guideline does not introduce any points, credits, or a weighting system. Interactions considered are described one by one, followed in parts by short paragraphs summarizing implications for the design of buildings and their technical systems. For example, the section on interaction between temperature and reactions to VOC points to the following implications. In case the VOC concentration cannot be minimized, lower temperatures should be aimed at (as compared to low-VOC indoor environments) to reduce adverse responses by occupants. In indoor environments with desired or existing higher temperatures, it is even more critical to select low-emitting materials.

The most detailed interactions described relate to the thermal indoor environment. Starting with interactions between various aspects of the thermal environment such as metabolism and temperature (or clothing and temperature), this section covers interactions between thermal indicators and IAQ (composition of the air, perception of IAQ, VOCs, biological components, particulate matter from heating equipment), lighting, and acoustics and their implications for human perception. Noteworthy are processes such as the breakdown of dust into finer particles on surfaces of the heating system and how this can potentially lead to increased irritation of occupants and the waste heat by lighting fixtures emitted to the room. This shows the relevance of interactions not only between the physical indicators of the IEQ, but also the interactions between selected building components and their unintended effects on IEQ and its perception. The sections on IAQ, visual, and acoustic indicators and their interactions follow the same pattern. First interactions between indicators of the corresponding domain and implications for design and operation are described, followed by further examples of cross-domain interactions not covered in previous sections.

Overall, the ASHRAE Guideline 10 reflects the current state-of-art in research regarding multi-domain IEQ in a clear and honest way. It does not pretend that the effect of interactions between IEQ domains are known, but clarifies already in the foreword that "current knowledge on interactions between and among factors that most affect occupants of indoor environments is limited" as recently confirmed by a comprehensive review [2]. The lack of consensus and available systematic research logically results in the absence of performance indicators or criteria. ASHRAE Guideline 10 refers to but does not include ranges or values of domain-specific guidelines or standards. Thus, the question arises whether a combination of the typologies of guidelines, schemes, and standards described in this section (i.e., DGNB, LEED, WELL, ASHRAE Guideline 10) can point to a way forward for a satisfying multi-domain IEQ standard.

3.8. EN 15232

3.8.1. Background and Objectives

In contrast to the above standards and schemes, the European standard "Energy Performance of Buildings—Impact of Building Automation, Controls, and Building Management" EN 15232 [13] does not focus on the design and retrofit of new and existing buildings, but is concerned with building operation. It was first published in 2007 in order to support the European Energy Performance of Buildings Directive (EPBD). The standard describes centrally applied Building Automation Control Systems (BACS) of which a number of items are related to room automation (RA) and occupant interfaces for indoor climate control. The standard specifies BACSs and RA functions, which have an impact on the energy performance of buildings and define minimum functional requirements for control and energy monitoring. RA functions are integrated to control IEQ domains in building automation concepts.

3.8.2. Quality Aspects, IEQ-Relevant Domains and Indicators

IEQ domains addressed by the standard include thermal comfort (control of thermal energy flows, supply air temperature, solar shading control), indoor air quality (demand control), and lighting (electrical lighting, glare blind control). The standard does not define any level of comfort or requirements regarding specific indicators of IEQ domains. However, it sets requirements with regards to minimum degree of control and links this to so called energy-efficiency classes, i.e., from highest (A) to lowest (D) energy efficiency. As such, the standard intervenes considerably in the degree of personal control occupants perceive in indoor spaces. The underlying assumption of EN 15232 [13] is that the higher the degree of automation, the higher the energy efficiency. Not addressed explicitly is the standing of energy-efficiency-driven building automation and management in the context of occupants' perception of and control over indoor climate [61].

3.8.3. Evaluation Method and Relation to Other Domains

No interaction between the control of different domains is mentioned, these are listed one after the other. EN 15232 represents the building automation/building energy management branches' perspective on multi-domain factors. It illustrates how the realization of IEQ domain requirements (see, for example, EN 15251 [19]/EN 16798-1 [62]) is interpreted by building automation engineers.

3.9. Concluding Reflections about the Selected Schemes

The preceding perusal of selected multi-criteria schemes and procedures for building evaluation and certification is by no means suggested to cover all existing instances in this category. Nonetheless, the selected cases do provide a useful overview of the state of affairs in this area. They include, in principle, multiple quality aspects (e.g., energy, resources, economy, indoor environment, social issues). Specifically, the main concern of the present contribution, namely buildings' IEQ, is explicitly addressed in all selected instances. Moreover, the multi-domain nature of occupants' exposure to buildings' indoor environments is recognized, as evidenced by the fairly consistent inclusion of thermal, visual, auditory, and olfactory components of the exposure. Nonetheless, the review of these schemes raises a number of critical questions and challenges. For one thing, from the fact that multiple domains are nominally included in the majority of the reviewed schemes, it does not follow that the implemented details are consistent across the board. This is especially true in view of the diverse and often inconsistent manner in which proxies and indicators are selected and treated in each domain. A case in point is thereby the degree of personal control (perceived control), which arguably plays an important role in evaluation processes of indoor environments [61,63–65]. However, the majority of the studied standards do not address design issues concerning personal control. Whereas Miljöbyggnad [10] does not consider personal control, WELL does address user control of windows and lighting [11]. The DGNB includes as such the personal control category ("user influence") as relevant to thermal comfort, ventilation, and lighting in their evaluation system [8]. However, this inclusion is limited by the assumption of a large number of digital user control interfaces. ASHRAE 10 [12] elaborates on the positive effect of personal control on user satisfaction. It also mentions relevant constraints (e.g., noisy outdoors deterring occupants from operating the windows). However, it does not address this related to the personal control potential for influencing interactions. LEED includes the evaluation option of personal lighting control, but not temperature or ventilation control [9]. It is not clear why a scheme may consider user control of the lighting system as a pertinent quality criterion, but not temperature or ventilation control. EN 15232 does not provide requirements or indicators for evaluating available degrees of control [13]. Such occurrences may be the consequence of the construction practices in a scheme's country of origin.

The motivation behind a majority of the efforts related to the reviewed schemes appears to be the provision of incentives to pertinent stakeholders and the community at large to raise consciousness and pay more attention to building quality. Credit-based quality evaluation and certification systems may indeed play a role in popularization of the building quality discourse and hence incentivize higher levels of intellectual and monetary investment in building design and operation. This motivation could also explain an underlying rather reductive tendency in the studied schemes. Thereby, presumably comprehensive and detailed evaluation procedures frequently result in rather simplistic quality labels (e.g., gold, bronze, silver). Such a simplification may make sense from the strategic, psychological, promotional, or policy-related perspectives, but it is not necessarily accompanied by transparent, objective, and scientifically based methods.

In this context, a central challenge pertains to the aggregation of evaluation results from individual categories or domains into overarching and unified ratings. Whereas the quality evaluation in individual categories is—at least in part—argued based on pertinent single-domain standards, the process of score aggregation into whole-building quality labelling remains frequently opaque, if not arbitrary. In the absence of hard and fast factual reasoning, the distribution of points and associated weights to different categories in rating schemes may be motivated by other factors, such as political ones. For example, when the DGNB system (for offices) was launched in 2009, summer thermal comfort had a higher weight than winter thermal comfort. This was motivated by the building and construction authority's intention to improve the summer heat protection of offices (DGNB [8]/BNB version 2009 [66]). More generally, rating schemes can be arguably influenced by value systems or political considerations. For instance, the degree of acceptance and adaptation of a scheme could depend on the fraction of the buildings in a specific (local or national) context that would obtain a successful rating.

These observations highlight the need for an overall reassessment and possibly re-thinking of the purpose, design, and handling of building evaluation, rating, and certification systems. Thereby, a central recurrent challenge remains the degree to which the multiplicity of evaluation criteria in general and the multitude of indoor-environmental domains in particular can be reduced into aggregated measures of building quality.

4. Where Do We Go from Here?

The discussion of schemes for total building quality evaluation and rating needs to take multiple viewpoints into consideration. There are arguments both in favor and critical of current practices in this area. Favorable comments suggest that building quality rating schemes, notwithstanding any weak points or flaws, serve important purposes. A positive impact is seen in raising the consciousness level of the stakeholders with regard to buildings' functional, environmental, social, and economic performance. Further implied positive effects pertain to the promotional and prestige benefits associated with achieving a high rating. Such accolades may also translate into competitive advantages and incentivize higher investments. On the other hand, it has been noted that formal rating schemes are prone to—and may be even encourage—"gaming". The contention is that, once a certain credit-based system is established, it might be exploited in terms of numeric maneuvering aiming at identifying the "cleverest" (or the cheapest) way to maximize the number of points earned, instead of focusing on truly essential measures.

There are, however, issues beside improper appropriation possibility that need to be addressed when reflecting on the current state and future development of building quality rating schemes. A central topic thereby is the previously mentioned challenge of integration. In other words, the procedures by which the rating schemes distribute, weight, and aggregate points related to different performance indicators in different quality categories are arguably neither consistent nor evidence-based. Of course, one could argue, that even in the case of the conventional single-domain standards, the mandated requirements (often expressed in terms of the minimum, maximum, or optimal values of assorted performance indicators) are not necessarily and completely evidence-based [67]. But one can—at least in case of indoor-environmentally relevant domains—trace such mandates back to some material from medically or physiologically based studies and experiments. Definition of maximum exposure times and levels to industrial noise, limitation of the maximum glare intensity, identification of tolerable ambient temperature ranges, or specification of maximum concentration of air pollution proxies may not be in all cases non-controversial. However, there is a certain consensus as to the nature of the underlying empirical evidence and the mode of translating the associated knowledge into IEQ specifications. As such, the majority of the schemes, which were discussed in the preceding review, refer to single-domain standards when treating the individual domains they consider. The case that can be made, at least to a certain extent, for the empirical legitimacy of single-domain standards, cannot be made for the rating systems and schemes that aim at integrated building quality evaluation encompassing multiple domains and their respective performance indicators. Here, the state of knowledge is simply wanting [2,12,67,68].

These observations underline the need for rigorous empirical investigation of the cross and combined effects of multiple influence factors from multiple domains. Short of such studies and the insights they could provide, the efforts toward holistic rating of indoor environments' quality in view of their effects on people's health and comfort remain limited and ultimately unconvincing. As such, a solid empirically based understanding of cross-domain effects of indoor-environmental exposure is arguably indispensable. The question remains though, if there are still good arguments for the continued application of the kinds of point-based building quality rating systems discussed in the present contribution, even though their embedded weighting procedures may be rather opaque.

We already mentioned arguments in the consciousness raising and quality popularization categories. Translating obtained higher quality rankings into market-relevant values (e.g., achieving higher revenues when real-estate properties are sold or let) constitutes another common argument. A further argument could be made in defense of existing rating procedures, not as an exact and detailed documentation of buildings' quality in general and indoor-environmental performance in particular but as a rough aggregate estimate, suitable, for instance, for coarse quality pre-screening or classification of a given building stock. In fact, there are numerous instances of application of pragmatic aggregate measures (also referred to as indices or scales) in areas such as social sciences, economics, or public policy. But for this argument to have any traction, at least three conditions must be met. First, the pragmatic nature of the rating procedure and result needs to be clear to all stakeholders involved. Strictly speaking, the rating systems are not to be thought of as measuring a pre-existing objective attribute (total building quality). Rather, they should be seen as constructing, to a certain degree, the entity they embark on measuring. Second, the effort, details, and expenses needed to conduct the rating should be of reasonable extent. In other words, it should be commensurate to the intended utility of the results, if they are understood as coarse indicators of building quality. Last and most importantly, the process delineated by—and the reasoning underlying—the rating systems must be of outmost transparency, and their results must be independently reproducible.

These observations imply the importance of a two-fold strategy in view of future developments in the area of multi-domain quality evaluation of built environments. The first, rather short-term strategy, needs to improve on certain key features of the existing—typically point-based—evaluation and ranking schemes. Such improvements should entail the provision of a transparent reasoning behind the point allocation process and employed weighting schemes. This would enable the users and stakeholders to better understand and gauge the underlying logic behind the numeric characteristics of the scheme's assessment procedures. The second, rather long-term strategy, must address the critical need for a deeper theoretical understanding of combined influences of multiple environmental parameters on people's perception and evaluation of the quality of indoor environments. This deeper scientific understanding of the relevant processes is understandably a gradual and iterative process, but it is the key condition for future instances of truly multi-domain building quality definition and assessment standards and guidelines.

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